Optical OCDMA enhanced by nonlinear optics

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ABSTRACT

Intended for the next generation of optical access networks, OCDMA is of great interest to meet the demand of increasing the number of users per access fiber, especially as spectral phase coding increases its performance in the optical domain. This, however, requires handling broad spectra and short pulses, which are best dealt with using opto-electronic or all-optical devices instead of slower electronics. Among others, we demonstrate spectral-phase-coded OCDMA using a fiber-based saturable absorber as thresholding in the receiver.

Keywords: OCDMA access networks, spectral slicing, spectral phase encoding, fiber Bragg gratings.

1. INTRODUCTION

The continued development of innovative high-bandwidth services aimed at the general public, such as online social networking, video on demand, "triple-play" packages, keeps the expectations of data communication network users on the rise. An ever-renewed need for speed must be satisfied, and the bottleneck to be lifted is currently in the "last mile", namely in access networks.

The solution chosen by most carriers, currently being deployed, is optical fiber to the end-users' premises. However, while a single fiber's enormous capacity is more than sufficient for a typical number of users in current access networks, sharing this huge bandwidth flexibly among many people remains an active research topic.

Currently-deployed passive optical networks (PONs) such as EPON and GPON typically share up to 2.5 Gbps among 16 to 64 users, for a single-user bandwidth on the order of 100 Mbps, using time-division multiplexing (TDM) [1]. To increase tomorrow's and longer-term PONs' multiplexing performances, prime candidates are wavelength-division multiplexing (WDM), then optical code-division multiple access (OCDMA) [2, 3]. Both these techniques can benefit from all-optical functionalities, especially to avoid managing multiple laser sources for different wavelengths, or to process code sequences faster than available electronics.

In the framework of the French National Agency for Research (ANR) project Supercode, we demonstrate experimentally an OCDMA transmission system, using a nonlinear-optics-generated continuum source, OCDMA encoders and decoders based on fiber Bragg gratings (FBG), for two different coding techniques.

2. OPTICAL CDMA TECHNIQUES

A typical OCDMA transmission link differs from a classical OOK optical link by an encoder/decoder pair: the encoder applies a code sequence (0 and 1 "chips") onto each modulated bit; a matched decoder reconstructs the data bits and filters out the code sequences of other users, except for residual multiple access interference (MAI). We will focus on optically-generated code sequences, where the optical energy in each bit is spread over the time or frequency domain to create the code sequence, using an all-optical device.

For instance, in a direct-sequence OCDMA (DS-OCDMA) setup, the coded signal is unipolar, similarly to on-off keying (OOK): the "1" chips are materialized by a nonzero intensity. A way to implement this optically is to start from a pulsed OOK signal; the encoders then split each optical pulse representing a mark into a succession, in the time domain, of several weaker pulses which materialize "1" chips. The encoders are then equivalent to a splitter, delay lines, and a combiner. This functionality has been demonstrated using many techniques, especially superstructured FBGs [4]. Decoders follow the same scheme, collecting part of the chip energy into a higher pulse. However, the decoded signal presents a high MAI level, and is sensitive to the source's optical coherence. [5]

Alternatively, in a spectral coding setup, a broadband optical signal is used, and the code is applied to selected spectral sub-bands within that bandwidth. For instance, in a spectral phase encoding (SPE) scheme, a chip-dependent phase shift is introduced into given spectral sub-bands; decoding is performed by applying the

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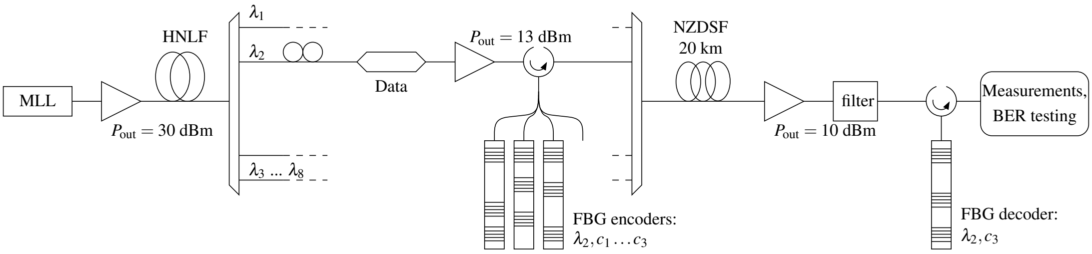

Figure 1. WDM/DS-OCDMA transmission setup using a sliced continuum source.

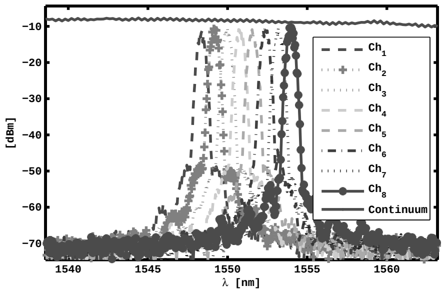

Figure 2. Continuum spectral slicing.

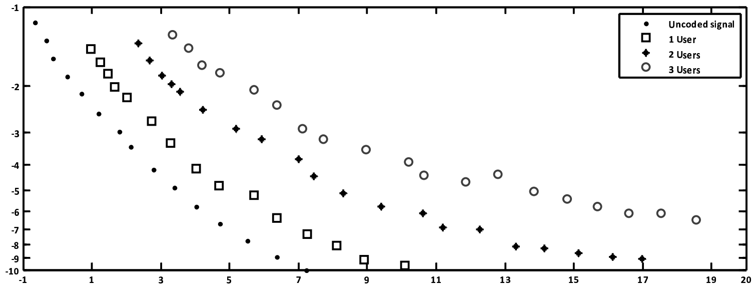

Figure 3. DS-OCDMA transmission: $\log_{10}(BER)$ *vs OSNR (dB).*

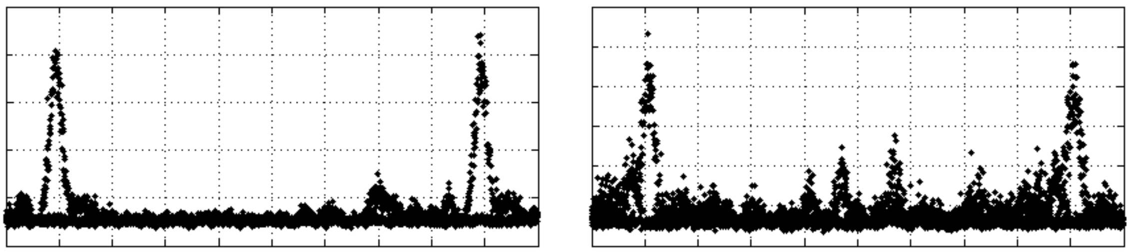

Figure 4. DS-OCDMA signal after decoding (X-axis: 200 ps/div; Y-axis: a.u.). (left): single user; (right): 3 users.

opposite phase shift [6]. The coders for such setups may be implemented by FBGs [7] or arrayed waveguide gratings (AWGs) [8]. Such spectrum-based techniques require that the signal have a wide enough band to discriminate the different frequency chips, thus need a broad optical source.

Nonlinear optics have long been proposed to perform processing functionalities faster that electronics or with better parallelism. They can also enable better OCDMA implementations [6]. For example, the aforementioned broad optical source can result from a continuum generated through spectral broadening of short pulses [3, 9]. This can also be used for slicing WDM channels in addition to OCDMA [10, 11]. Finally, a Mamyshev-like regenerator can serve as a thresholder in the optical domain to alleviate MAI-induced crosstalk between OCDMA channels at the reception [12].

3. SPECTRAL SLICING FOR WDM/DS-OCDMA

Our continuum source [11] consists of a spectrally broadened 10-GHz pulse train originating from a Pritel mode-locked laser (MLL), boosted to an average power up to 30 dBm by a fiber amplifier, then propagated through a 500-m long OFS highly nonlinear fiber (HNLF). Working in the normal dispersion regime has enabled the generation of a wide flat supercontinuum (spectral width of 35 nm) having a high spectral energy density and an improved stability (results shown in Fig. 2) [13]. Spectral slicing by a 8-port WDM demultiplexer, with a 100 GHz channel spacing and a gaussian 50 GHz channel bandwidth, yields nearly transform-limited gaussian pulses between 8.9 and 11.4 ps long.

These pulses, at each desired wavelength, may be used for an OCDMA link; Fig. 1 shows the experimental setup where a single wavelength is used for data, and the remaining 7 are transmitted unmodulated. The 10-GHz pulse train at $\lambda_2 = 1549.31$ nm is converted, using a conventional MZI, to a RZ-OOK 1.25 Gbps pseudo-random binary sequence ($2^7 - 1$ PRBS). This modulated signal is injected, through an optical circulator and 1×4 splitter, into three DS-OCDMA encoders. The transmission over 20 km of nonzero-dispersion-shifted fiber (NZDSF) amounts to a 80 ps/nm maximum emulated dispersion.

The DS-OCDMA encoders that we used are FBG devices, designed for an extended quadratic congruence (EQC) code family [5] with parameter $p = 5$, code length $L = 45$, chip length $T_c = 10$ ps, at λ_4. Figure 4 shows oscilloscope traces of the decoded signal with and without interferers. In the latter case, MAI impairs data reception, as can be seen in Fig. 3: the penalty when increasing the number of users is several dB, and an error

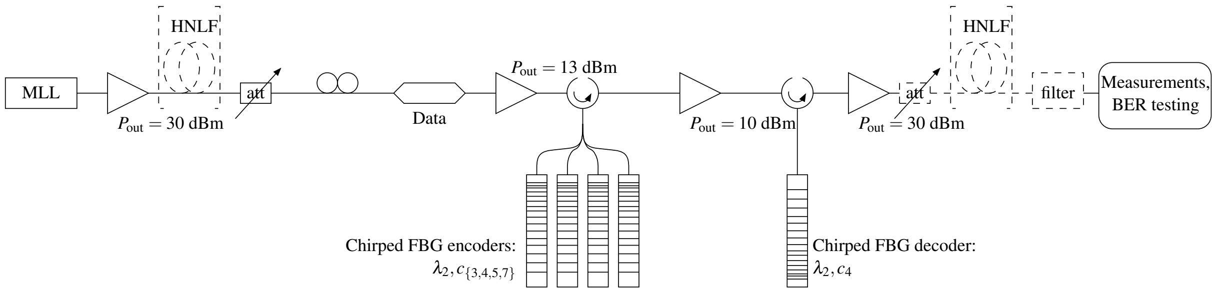

Figure 5. SPE-OCDMA setup: with or without continuum generation; with or without nonlinear thresholder.

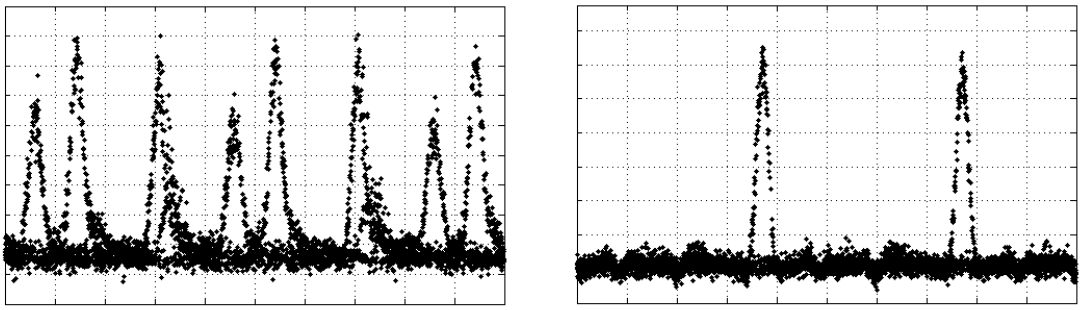

Figure 6. SPE-OCDMA signal. (X-axis: 200 ps/div; Y-axis: a.u.). (left): decoding only; (right): with thresholder

floor at about 10^{-6} occurs for 3 simultaneous users.

4. SPE-OCDMA WITH NONLINEAR OPTICAL THRESHOLDER

Unlike DS-OCDMA, SPE-OCDMA is a bipolar coding scheme, essentially scrambling the phase of a short pulse, dramatically spreading it in the time domain. Decoding is done by applying the opposite phase shifts to the same spectral sub-bands as the coding; signals from other users thus retain phase shifts over other sub-bands, and do not reform into short pulses. Therefore, the MAI remains lower than for DS-OCDMA, and multiplexed coded signals have a better orthogonality.

We have realized encoders and decoders based on chirped FBGs, through a photowriting process detailed in [14], with 0.3-nm wide spectral sub-bands for the chips. The codes chosen are Walsh-Hadamard (WH); since they are applied in the spectral domain, their orthogonality is not dependent on synchronicity. Our coders are 8 chips long, leading to a 2.4 nm total spectral width, although our 35-nm continuum could in principle support 100-chip long codes; alternatively, shorter codes could be combined with WDM multiplexing of narrower-spectrum signals.

Consequently, in our setup, the HNLF is actually not needed at the source, as spectral broadening in the 30-dBm EDFA is sufficient for a single WDM channel. This is illustrated in Fig. 5, where an optical attenuator is placed after said EDFA to ensure that the spectral power density is the same as if the HNLF had been used to generate a full-spectrum continuum.

Fig. 7 shows the autocorrelation of signals (generated from the continuum source) ran through four different WH encoders and one decoder. The dark blue curve (C4D4) corresponds to a matched coder and decoder; the central peak is significantly higher than the central or secondary lobes of other curves, indicating a low MAI.

However, in Fig. 6 (left), the oscilloscope trace of the decoded signal with 3 interfering users shows that the multiplexed channels cannot be separated. This is due to the limited bandwidth (10 GHz) of the photodetector before the oscilloscope, which broadens the pulses, lowering their peak power [15].

Thus, MAI suppression has to be performed in the optical domain. A Mamyshev-style regenerator can be used as an all-optical thresholder, exploiting the high peak power of the pulses after OCDMA decoding. Figure 6 (right) shows the same eye diagram as previously, except with thresholding using a second 30-dBm EDFA followed by an HNLF. MAI is extinguished, and Fig. 8 shows a penalty of less than 4 dB for 4 simultaneous users, without an error floor.

This SPE-OCDMA setup with thresholder therefore has a good performance. A significant drawback, however, is the requirement of a high-power optical amplifier after decoding in order to reach an adequate peak power threshold. In an actual access network, this functionality would require a device with a higher nonlinearity than the off-the-shelf HNLF that we used. This also limits the transmission, as peak power is extremely sensitive to uncompensated dispersion, precluding transmission even over NZDSF.

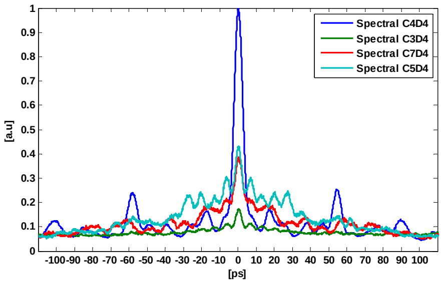

Figure 7. Autocorrelation after matched (C4D4) and mismatched decoding.

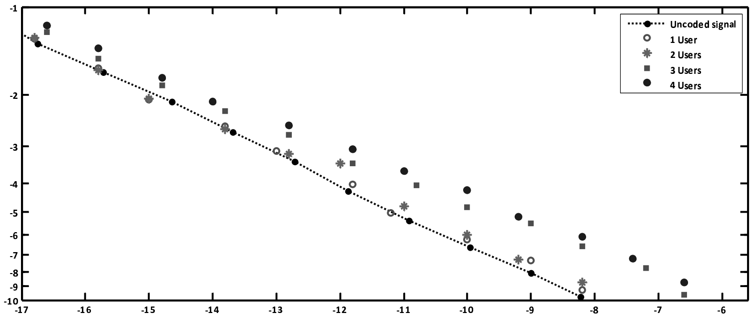

Figure 8. SPE-OCDMA transmission: $\log_{10}(BER)$ *vs OSNR (dB).*

5. CONCLUSIONS

OCDMA implementations can benefit from nonlinear optical functionalities. Notably, we have demonstrated integration of a broadband source into proof-of-concept WDM/DS-OCDMA and SPE-OCDMA links, and thresholding in the optical domain.

These functionalities should be further improved using higher nonlinearity devices, possibly photonic crystal fibers. Also, this setup supports higher data rates and/or longer code lengths, thus a better multiplexing capacity.

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